

## A SEDIMENT BUDGET FOR AN URBANIZING WATERSHED, 1951-1996, MONTGOMERY COUNTY, MARYLAND, U.S.A.<sup>1</sup>

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**ABSTRACT:** Despite widespread interest, few sediment budgets are available to document patterns of erosion and sedimentation in developing watersheds. We assess the sediment budget for the Good Hope Tributary, a small watershed (4.05 km<sup>2</sup>) in Montgomery County, Maryland, from 1951-1996. Lacking monitoring data spanning the period of interest, we rely on a variety of indirect and stratigraphic methods. Using regression equations relating sediment yield to construction, we estimated an upland sediment production of 5,700 m<sup>3</sup> between 1951 and 1996. Regression equations indicate that channel cross-sectional area is correlated with the extent of development; these relationships, when combined with historical land use data, suggest that upland sediment yield was augmented by 6,400 m<sup>3</sup> produced by enlargement of first-order and second-order stream channels. We used dendrochronology to estimate that 4,000 m<sup>3</sup> of sediment was stored on the floodplain from 1951-1996. The sediment yield from the watershed, obtained by summing upstream contributions, totals 8,100 m<sup>3</sup> of sediment, or 135 tons/km<sup>2</sup>/year. These results indicate that upland erosion, channel enlargement, and floodplain storage are all significant components of the sediment budget of our study area, and all three are approximately equal in magnitude. Erosion of "legacy" floodplain sediments originally deposited during poor agricultural practices of the 19th and early 20th Centuries has likely contributed between 0 and 20% of the total sediment yield, indicating that these remobilized deposits are not a dominant component of the sediment yield of our study area.

(KEY TERMS: sediment budgets; urbanization; channel enlargement; floodplain stratigraphy.)

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### INTRODUCTION

Urbanization causes profound changes in patterns of erosion and sedimentation in watersheds. Impervious surfaces and compacted soils increase runoff (Leopold and Skibitzke, 1967; Hollis, 1975; Sauer *et al.*, 1983), leading to bank erosion, channel

enlargement, and channel incision (Hammer, 1972; Morisawa and LaFlure, 1979; Arnold *et al.*, 1982; Peck, 1986; Neller, 1988). Upland sediment production may dramatically increase during construction, but after construction has ceased, buildings, lawns, and roadways are widely believed to produce relatively little sediment (Dawdy, 1967; Wolman, 1967; Wolman and Schick, 1967).

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These changes can have important effects on riparian ecosystems and on downstream regions. Changes in flow regime associated with urban development can have dramatic effects on the structure of ecological communities and the rates of biological processes (Poff and Nelson-Baker, 1997; Palmer *et al.*, 2002; Nilsson *et al.*, 2003). Higher percentages of impervious surfaces in a watershed, for example, may be associated with decreases in invertebrate species richness (Moore and Palmer, 2005), and increased suspended sediment concentrations can have numerous important ecological effects (Waters, 1995). In downstream areas, changes in nutrient and sediment loading can adversely affect receiving waterways; this is a significant concern in the watersheds that drain to the Chesapeake Bay (Brush, 1989; Cronin and Vann, 2003; Kemp *et al.*, 2005).

Despite the importance of documenting changes in sediment budgets caused by urbanization, relatively few studies have attempted to quantify the separate components of sediment production and storage in urbanizing watersheds. Wolman (1967) documented the effects of urban development on some sediment budget components, but this pioneering study is not a complete sediment budget. Other studies describe important geomorphic processes such as bank erosion rates and changes in channel morphology (Hammer, 1973; Hession *et al.*, 2003), changes in bed material grain size or bed morphology (Pizzuto *et al.*, 2000), channel incision (Booth, 1990), and sediment yield (Dawdy, 1967), but these studies present only a partial account of patterns of sediment production and storage in urbanizing watersheds. A study by Trimble (1997) remains one of the few published sediment budgets of urbanized watersheds.

There are several explanations for the lack of detailed sediment budgets for urban areas. First, sediment budgets traditionally rely on direct observations spanning several decades. These data are rarely available. Furthermore, when the results of such studies are needed, decisions must typically be made in a short time period, so starting a monitoring program is rarely practical, and, as a result, direct observations are almost never available to assess urban sediment budgets. Second, gaging station data for sediment and water discharge are often unavailable (Wahl *et al.*, 1995), so historical data needed to close sediment budgets is difficult to obtain. Finally, available models for predicting upland sediment yield and other components of sediment budgets are typically not calibrated or designed for urban watersheds. The Watershed Erosion Prediction Project (WEPP) model, for example, has been designed for agricultural, rangeland, and forest watersheds, and cannot be readily applied in urban settings (see <http://topsoil.nserl.purdue.edu/nserlweb/weppmain/>).

In this study, we present a sediment budget for a third-order watershed in Montgomery County, Maryland, for a 45-year period. During this time, land use in the watershed changed from predominantly agricultural to suburban. Lacking direct observations of hydrology, sediment transport, or channel morphology for the entire 45-year period, we used land-use data, computations of historical peak discharges, statistical models based on short-term geomorphic surveys, and the ergodic assumption (Bloom, 1998) to estimate sediment budget components.

Our methods are adopted to answer specific questions regarding the sediment budget of an urbanizing watershed. These questions are as follows: (1) Does erosion of the channel boundaries provide a significant fraction of the sediment yield from the watershed? (2) Is floodplain storage through overbank deposition significant? (3) Do upland surfaces produce a significant amount of sediment?

The answers to these questions have important management implications. Fortunately, even imprecise estimates of sediment budget components can provide useful information to managers (Reid and Dunne, 2003). The somewhat novel methods adopted during this research, though perhaps less accurate than more traditional methods, provide at least one example of how to assess sediment budget components in the absence of continuous monitoring or gaging station data.

### *The Study Area*

The Good Hope Tributary is a third-order stream in the Anacostia River watershed that is situated on the eastern edge of the Maryland Piedmont Geomorphic Province (Thornbury, 1965) (Figure 1). Suburban and urban development has occurred on upland areas, while the hillslopes and valley bottoms have remained forested. The maximum relief of the watershed is about 60 meters. The relief ratio of the watershed, defined as the basin length (the straight-line map distance between the mouth of the stream and the farthest point on the drainage divide) divided by the maximum relief, is 0.019. The bed of the Good Hope Tributary has an average gradient of 1.33% and it consists mostly of gravel sized sediment (Lewicki, 2005). The banks consist predominantly of sandy mud with <10% gravel (grain size terms are used following the Udden-Wentworth scale; Lewis, 1984). The Hollywood Tributary is a neighboring second-order stream with a similar drainage basin area, but more extensive suburban development than the Good Hope Tributary (Figure 1).

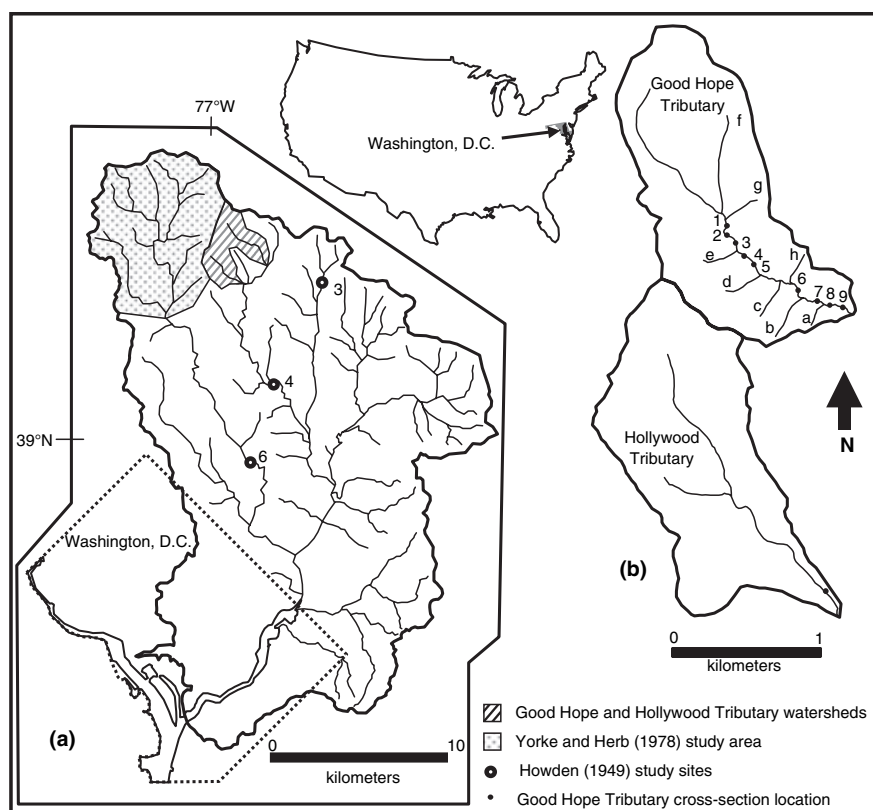


FIGURE 1. Location Map of the Good Hope Tributary Study Area Near Colesville, Maryland. (a) The Anacostia River watershed showing research areas of this study and other relevant studies. (b) The study area of the current study with a larger scale, showing locations of first-order tributaries and cross-sectional survey locations.

### Land Use History of the Maryland Piedmont.

Prior to the arrival of English settlers in 1608, the Maryland Piedmont was covered by hardwood forests, which gave rise to a thick, organic-rich O horizon on floodplain soils. The heavily forested watersheds were likely covered with forest litter, minimizing the influence of overland flow, producing long, low-storm hydrographs (Jacobson and Coleman, 1986). Palynological studies at the mouth of the Patuxent River demonstrate that sedimentation rates in the estuaries during this time interval were low (on the order of 1 mm per year; Pasternack *et al.*, 2001) suggesting that sediment yield in the natural condition was low.

Following European settlement and the development of agriculture, excessive erosion occurred on upland surfaces of the small watersheds of the region (Costa, 1975). This created sediment yields four times higher than they were prior to settlement by Europeans (Costa, 1975). Much of this sediment was stored on floodplains in low-order watersheds (Costa, 1975; Jacobson and Coleman, 1986).

Following World War II, suburban growth around Washington, District of Columbia, and Baltimore accelerated (Jacobson and Coleman, 1986). In the

1970s, Montgomery County was one of the most rapidly urbanizing counties in the nation, and during periods of active construction in the Little Patuxent watershed, suspended sediment concentrations increased significantly (Roberts and Pierce, 1974).

The results of these changes in land use are evident in alluvial floodplains of the Maryland Piedmont. Exposed cut-banks illustrate two different land use eras through three distinct stratigraphic units (Figure 2). The sequence shown in Figure 2 shows a thick layer of sediment from agricultural sources (Figure 2a) deposited immediately above the historical organic horizon of the pre-settlement forest floor (Figure 2b). Both of these units were deposited above a layer of coarse angular sediment that was most likely deposited during the slow lateral migration of the pre-settlement streams (Figure 2c) (Jacobson and Coleman, 1986).

The history of land use changes and associated alluvial sedimentation characteristic of our study area has also been described from the southeastern and Midwestern regions of the United States (U.S.) (Happ *et al.*, 1940; Trimble, 1964, 1977, 1983). The results of our study may provide some insights into sediment budgets of these areas as well.



FIGURE 2. Photograph of Cut-Bank Exposure in the Study Area. (a) Sediments from the Agricultural Age (Jacobson and Coleman, 1986). (b) A buried organic horizon from the pre-settlement forest floor. (c) Alluvial sediment deposited during lateral migration of the stream channel prior to European settlement.

### EFFECTS OF URBANIZATION ON PEAK FLOWS IN THE STUDY AREA

Urbanization causes extensive changes in hydrologic processes, including increased peak flows and decreased low flows (Leopold and Skibitzke, 1967; Hollis, 1975; Sauer *et al.*, 1983; Moglen *et al.*, 2004). Long-term hydrological monitoring data are not available for the study area, but several modeling studies provide a useful context for evaluating hydrological changes in the region caused by urban development. In a study of Watts Branch, an urbanized watershed in Montgomery County, Maryland, Beighley and Moglen (2002) presented hydrological modeling results suggesting that the two-year peak discharge increased by factors from 1.3 to 3.0 from 1951–2007 for second-order subwatersheds similar in size to the Good Hope Tributary. A similar analysis was presented by Palmer *et al.*

(2002) for the NW Branch watershed from 1951 to 1997. The NW Branch watershed is immediately adjacent to the Good Hope tributary. Palmer *et al.* (2002) reported that peak discharge in second-order subwatersheds of the NW Branch increased by factors from 1.3 to 7.7. The variability in these predictions is largely controlled by the extent of impervious cover associated with urbanization in each subwatershed.

### METHODS

A sediment budget reflects the balance between input, output, and changes in storage over a specified time period:

$$\text{Input} + \Delta\text{Storage} = \text{Output} \quad (1)$$

We apply Equation (1) to the Good Hope Tributary from 1951 to 1996. We chose this period because of the availability of topographic maps and aerial photographs, and also because it spans a period of significant urbanization of the watershed.

The sediment budget is formulated in two separate steps (Figure 3). First, a budget is formulated for each of the nine first-order tributaries (Figure 1). Because first-order tributaries supply sediment to the main channel of the Good Hope Tributary, we can solve the budget equation for the output of first-order tributaries to provide the input term for the budget of the main channel of the Good Hope Tributary. The solution to the sediment budget for the main channel then provides estimates of the sediment yield from the watershed.

The sediment budget for first-order tributaries only includes two terms: upland sediment production and sediment production from channel enlargement. We neglect sediment storage in first-order tributaries because these streams lack floodplains, and also because bedrock is exposed along these channels. A similar approach was advocated by Costa (1975).

The sediment budget for the main channel of the Good Hope Tributary includes the net supply from first-order tributaries upstream, sediment production due to channel enlargement, and sediment storage on floodplains. We do not explicitly include changes in sediment storage on the bed of the main channel of the Good Hope Tributary, but we argue in the Discussion section of the paper that our methods implicitly include these changes.

Long-term stream gaging and monitoring data are not available for the study area, and therefore we used indirect methods to determine several components of the sediment budget. We also used regression equations

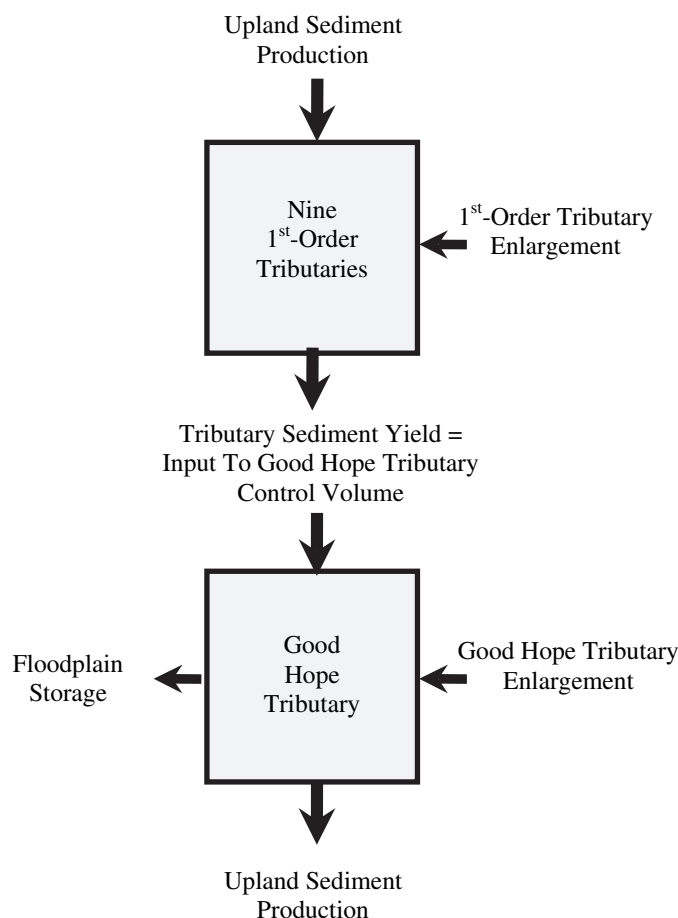


FIGURE 3. Schematic Two-Phase Sediment Budget Illustrating Control Volumes and Sediment Sources and Storage Areas.

previously published for the study area to relate annual upland sediment production to the percentage of construction in the watershed from each year from 1951 to 1996. Similarly, sediment production caused by channel enlargement was estimated from regression equations relating channel cross-sectional area to upstream land use. Changes in channel area between 1951 and 1996 were converted to sediment volumes by multiplying by the distance between sampling points (these methods are explained in greater detail below).

#### *Upland Sediment Production*

In developing our methods, we considered several different approaches for estimating upland sediment production. For example, we tried to adapt the WEPP (U.S. Department of Agriculture, 1995) model for use in our suburban study area (Schnick, 2005). We found, however, that because WEPP was designed for agricultural landscapes, and also because it was relatively cumbersome to use, that empirical methods were more convenient (and equally accurate).

We estimated sediment production from the uplands of the watershed by using an equation derived by Yorke and Herb (1978) for our study area:

$$\text{Log } Y_x = 0.059 C - 0.047 \quad (2)$$

where  $Y_x$  is the suspended sediment yield in tons per acre [Yorke and Herb (1978) worked in English units], and  $C$  is the percentage of land under construction. Equation (2) has a correlation coefficient of 0.47, and a standard error of estimate of about 62% (Yorke and Herb, 1978). Yorke and Herb (1978) measured sediment yield from 1962 until 1974. In 1962, sediment control measures were not in place, and sediment yields were high. In 1974, sediment yields had declined somewhat due to the use of a variety of sediment control techniques. However, the scatter in the observational data remained high, and Yorke and Herb (1978) found that  $C$  was the only useful independent variable for predicting suspended sediment yield (that is, explicitly including sediment control measures did not result in improved predictions). Thus, the use of Equation (2) for our study spans the development and application of sediment control methods. Equation (2) will likely underpredict sediment yields before the use of sediment control techniques, and it should overpredict sediment yields after these methods were in widespread use.

To apply Equation (2) to the Good Hope watershed, the percentage of the land under construction in each year was needed. We used historical tax map data, which indicate the year of construction for residential developments, to determine the area of the watershed under construction upstream from each node in the stream network. Spatial data quantifying the area extent of construction projects within the Good Hope Tributary watershed were acquired for each year of the sediment budget using the methods outlined by Moglen and Beighley (2002). Combining these data with a map of the stream network, the fraction of the watershed that was under construction upstream from the top of each first-order tributary was determined for every year of the sediment budget. These data were entered into Yorke and Herb's (1978) equation to determine the sediment yield for the uplands of each subwatershed for every year of the budget.

#### *Sediment Production by Enlargement of First-Order Streams*

The sediment budget of Figure 3 contains a term for sediment production related to erosion and channel enlargement of first-order tributaries. Unfortunately, there are no historical surveys available that can be used to directly assess the magnitudes of these

changes. Furthermore, the first-order tributaries of the Good Hope Tributary lack well-developed floodplains. Existing regression equations that relate land use to channel area, for example, those of Hammer (1973), only apply to channels with well-developed floodplains [as will be noted below, Hammer's (1973) equations are not accurate in the study area anyway]. As a result, we developed empirical methods based on survey data from the study area to estimate enlargement of first-order tributaries.

Thirty-five cross-sections were surveyed along first-order tributaries to the Good Hope Tributary (Figure 1) (Allmendinger, 1999). As noted above, first-order tributaries do not have well-developed floodplains, and therefore channel area was defined as the area of the cross-sections below the lowest break in slope between the adjacent hillslope and the channel banks (Figure 4). Fortunately, our results (presented below) lead to a very simple method for estimating the changes in cross-sectional area for first-order tributaries. Changes in cross-sectional area were multiplied by the length of each tributary to provide estimates of the volume of sediment produced by channel enlargement between 1951 and 1996.

#### *Sediment Production by Enlargement of the Good Hope Tributary*

Because the main channel of the Good Hope Tributary is bordered by floodplains, the methods used to

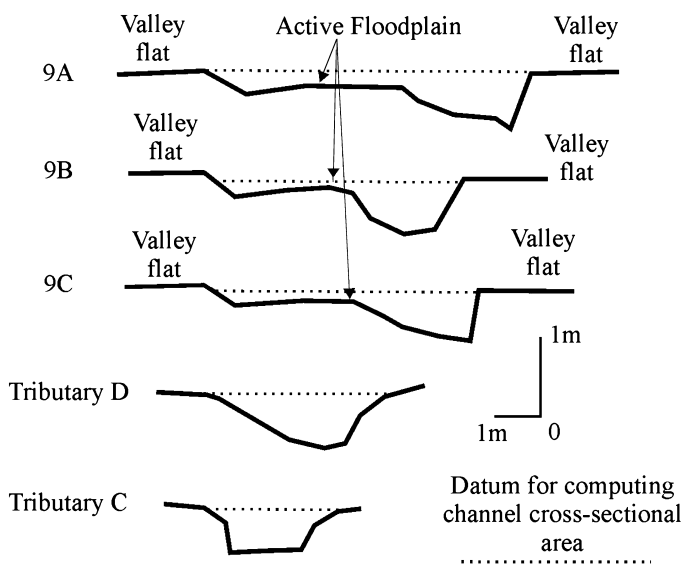


FIGURE 4. Typical Cross-Sections of the Good Hope Tributary Main Channel (Sites 9A, 9B, and 9C) and Tributaries (Allmendinger, 1999) (Figure 1). Examples of the valley flat and the active floodplain are also illustrated. The datum for computing the cross-sectional area of the channel is indicated on each cross-section.

assess sediment production by first-order channel enlargement needed to be modified before being applied to the Good Hope Tributary. We initially hoped to use existing regression equations developed by Hammer (1972, 1973) for the Philadelphia area. However, Hammer's equations were not able to predict the channel cross-sectional areas of the Good Hope and Hollywood Tributaries, so we developed our own regression equations that relate watershed area and imperviousness to channel cross-sectional areas. We then applied these regression equations to conditions in 1951, using estimates of the land use in the watershed at that time. The change in cross-sectional area is determined by subtracting the 1951 channel area from the 1996 channel area. The volume of sediment produced by channel enlargement is then estimated by multiplying the change in cross-sectional area by the distance between sampling sites.

To obtain data required to relate channel cross-sectional area to land use, we surveyed cross-sections in 1998. Using detailed criteria proposed by Hammer (1973), nine sites along the Good Hope Tributary and four sites along the Hollywood Tributary were selected (Figure 1). Two landforms were identified at each site, the valley flat and the active floodplain. The valley flat corresponds to the extensive area inundated during major flooding, while the active floodplain is a site of alluvial sedimentation related to lateral channel migration (these landforms are discussed in detail by Allmendinger, 2004). We used the elevation of the valley flat as a datum for calculating channel cross-sectional areas (Figure 4), because this approach provided the best correlation between channel area and land use (Allmendinger, 1999).

#### *Sediment Storage on the Floodplain*

Well-developed alluvial floodplains border the main channel of the Good Hope Tributary. We estimated sedimentation rates on the active floodplain and valley flat using methods outlined by Hupp and Bazemore (1993). Cores were taken from trees growing on the floodplain with an increment borer, and the annual growth rings were counted. Trenches were dug at a distance equal to two times the diameter away from the trunks of 92 trees. The thickness of the soil above the tree's original roots provides an estimate of the total sedimentation over the life of the tree.

Cores were extracted from 25 eastern hophornbeams (*Ostrya virginiana*), 18 tulip poplars (*Liriodendron tulipifera*), 11 red maples (*Acer rubrum*), nine flowering dogwoods (*Cornus florida*), nine eastern white oaks (*Quercus alba*), five northern red oaks (*Quercus rubra*), and four alternate leaf dogwood (*Cornus alternifolia*). The remaining six cores were

extracted from the only representative of their species found in the sample. These species include the eastern sycamore (*Platanus occidentalis*), mockernut hickory (*Carya tomentosa*), pignut hickory (*Carya glabra*), river birch (*Betula nigra*), witch hazel (*Hamamelis virginiana*), sweetbay magnolia (*Magnolia virginiana*), northern pin oak (*Quercus palustris*), and coastal plain willow (*Salix caroliniana*).

The method of Hupp and Bazemore (1993) is imprecise for several reasons. For example, tree roots do not always grow horizontally, and as a result, different values of accumulation might be obtained by measuring soil thickness at different distances away from the tree. Also, organic matter accumulates even in the absence of net sedimentation, so some material would cover the tree roots in upland settings that are not subject to deposition from floods. We address these concerns in two ways. First, as noted above, we carefully standardized the distance at which accumulation was measured, making sure to measure accumulation at a distance of two tree diameters away from the trunk. This approach should provide results that are consistent and comparable, at the very least. We did not directly address the second concern during this study. However, we use information from related studies in the mid-Atlantic region to assess the potential errors associated with the accumulation of *in situ* organic matter. This information is presented in the Discussion section.

Along the Good Hope Tributary, our results indicate that accumulation rates vary systematically with distance away from the channel (the evidence for this conclusion will be presented in the Results section of the paper). Therefore, when we determined the volume of sediment stored on the floodplain, we averaged the data in bins of 2 meters width to obtain a smoothed relationship between accumulation rates and distance from the stream channel. This function was then numerically integrated to determine the annual volume of deposition per unit valley width. The total volume of sediment stored on the floodplain was then computed by multiplying by the length of the valley and the duration of the sediment budget.

#### *Measurement of Watershed Characteristics*

The drainage basin area and the fraction of the watershed covered with impervious surfaces were determined for the Good Hope and Hollywood Tributary watersheds using 1:6,000 scale aerial photographs taken in 1996 and 1:24,000 scale USGS topographic maps (U.S. Department of Interior, 1951) of the watershed from 1951. The area of the watershed occupied by houses was determined by

counting all of the houses in each watershed and multiplying by 139.4 square meters, the area of a representative suburban house (James E. Pizzuto *et al.*, 2006, unpublished manuscript). The area of the watershed occupied by road surfaces was determined by measuring the linear distance of road surfaces within the watershed, dividing that number by the scale of the map or photograph, and multiplying by 6.1 meters, the width of a typical suburban street (James E. Pizzuto *et al.*, 2006, unpublished manuscript); corrections were applied for highways with more than one lane. The areas of schools, parking lots, and stores were digitized directly from the maps and aerial photographs (generally, these land uses were not present in 1952, so most of the digitizing was done from the 1996 aerial photograph). The fraction of the watershed covered with impervious surfaces was determined by adding the areas of houses, roads, and other types of impervious surfaces, and dividing by the area of the watershed.

#### *Historical Evidence for Channel Enlargement in the Study Area*

Because we lack detailed monitoring data, we sought alternative means of verifying our methods. Fortunately, we were able to locate historical evidence of channel enlargement in the Anacostia watershed, including photographs of streams as well as measurements of the water-surface width, maximum channel depth, and water velocity (Howden, 1949). Three of the sites documented by Howden (1949) were re-photographed and surveyed with an auto-level, stadia rod, and tape in 2002. We use the cross-sections to estimate the width of water surface in the present-day channel for the same depth of flow observed in 1949.

We were particularly pleased to discover Howden's (1949) work because of the lack of historical monitoring data in our study area. However, the limitations of his observations should be considered. Because his measurements are limited to water surface width, maximum depth, and velocity at base flow, his data are difficult to compare quantitatively to our surveyed cross-sections and to other methods that predict changes in bankfull cross-sectional channel area caused by urbanization. Our primary purpose in using Howden's data is to confirm that channels actually increased in size during the period of our study, and we use channel width as a metric to represent channel size because Howden's data provide an unambiguous means of estimating channel width. Howden's data cannot, however, be used to quantitatively evaluate our empirical methods for estimating bankfull channel enlargement.

## RESULTS

*Changes in Land Use Between 1951 and 1996*

In 1951, the areas associated with houses and roads in the Good Hope Watershed were 0.013 and 0.044 km<sup>2</sup>, respectively (Table 1). The total drainage area of the Good Hope watershed is 4.05 km<sup>2</sup>, making the impervious fraction of the 1951 watershed equal to 1.4%. In 1996, impervious areas for houses, roads, and other development accounted for 0.069, 0.129, and 0.106 km<sup>2</sup>, respectively, for an impervious fraction of 7.5%. The impervious fraction of the Hollywood Tributary was 3.6% in 1951 and 20.4% in 1996 (Table 1).

The fraction of the Good Hope Tributary watershed under construction from each year from 1951 to 1996 is presented in Figure 5. Construction activity occurred in three broad pulses. The first lasted from 1951 to about 1965, the second lasted from 1973 though about 1980, and the third and final pulse of construction lasted from 1983 to about 1990.

*Historical Evidence of Channel Enlargement*

The width of the water surface at Howden's (1949) three sites (Figure 1) increased significantly during the last 54 years (Figure 6, Table 2). The range of enlargement ratios is quite large, ranging from 1.06 along the Little Paint Branch to 3.56 along the Northeast Branch (the enlargement ratio as used here is defined as the width after urbanization divided by the width before urbanization).

*Enlargement of First-Order Tributaries*

When the cross-sectional areas of the first-order tributaries are plotted as a function of impervious fraction, two distinctive groups are apparent (Figure 7). Five tributaries have similar and relatively low cross-sectional areas. Four of these have large detention basins

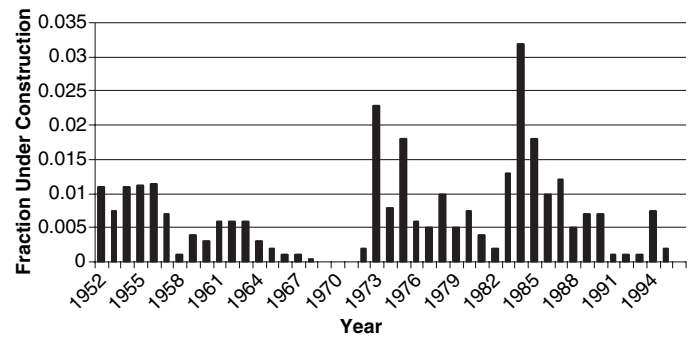


FIGURE 5. Fraction of the Good Hope Tributary Watershed Under Construction for 1951-1996 (from Lewicki, 2005).

in their headwaters, while the fifth (shown in gray in Figure 7) has an impervious fraction of 0 (i.e., no development has occurred in this watershed). These data suggest that no enlargement has occurred in these five watersheds. Because their cross-sectional areas are similar, the cross-sectional area of the undeveloped tributary was taken to be the cross-sectional area for all the tributaries in 1951. This suggests that the three first-order tributaries without detention basins have enlarged by factors of 2.1, 2.4, and 2.5 (Table 3).

*Enlargement of the Main Channel of Good Hope Tributary*

Regression analysis of data from the main channel and from the Hollywood Tributary resulted in Equation (3),

$$CA = 40.8FI + 0.823DA, \quad (3)$$

where CA is the channel cross-sectional area and has units of m<sup>2</sup>, FI is the fraction of the watershed covered with impervious surfaces, and DA is the drainage basin area and has units of km<sup>2</sup>.

Equation (3) has an adjusted  $R^2$  value of 0.74, and a significance ( $p$ ) of 0.004. Both variables are

TABLE 1. Land Use Characteristics of the Good Hope and Hollywood Tributary Watersheds.

	Good Hope Tributary 1951	Good Hope Tributary 1996	Hollywood Tributary 1951	Hollywood Tributary 1996
Drainage Area	4.05 km <sup>2</sup>		4.14 km <sup>2</sup>	
Impervious Area	Houses: 0.013 Roads: 0.044  0.057 km <sup>2</sup>	Houses: 0.069 Roads: 0.129 Other: 0.106  0.304 km <sup>2</sup>	0.149 km <sup>2</sup>	0.596 km <sup>2</sup>
Impervious Fraction	1.4%	7.5%	3.6%	20.4%

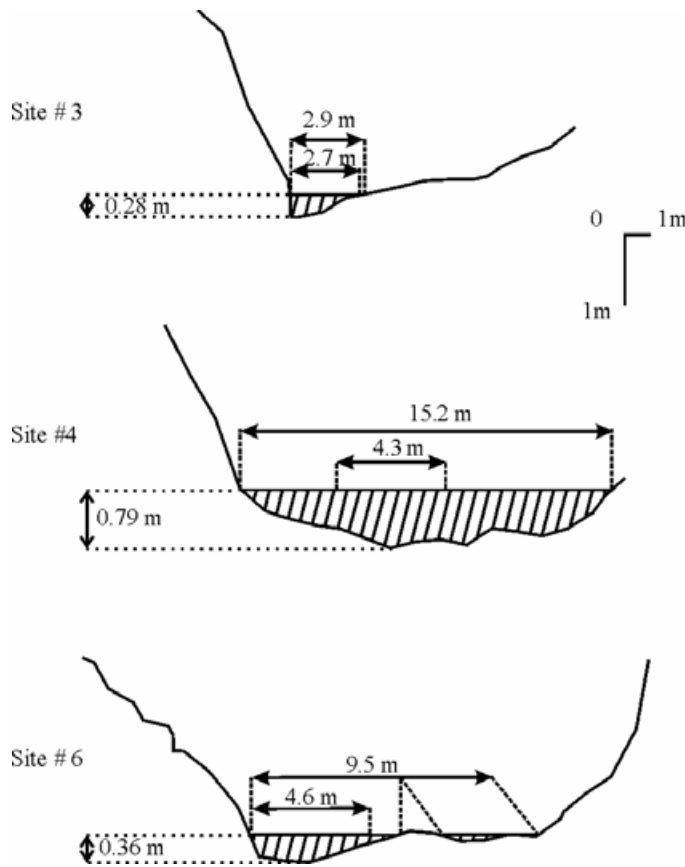


FIGURE 6. Surveyed Cross-Sections of Three Streams in Northern Prince George's County, Maryland. Channel depth and the lesser of the two widths are from Howden (1949), while the greater widths were measured from cross-sections surveyed in 2002 using the water depth measured by Howden, (1949) as a vertical datum.

TABLE 2. Changes in Width of Anacostia River Tributaries from 1949 to 2002.

Site #	1949		2002	
	Channel Depth (meter)	Channel Width (meter)	Channel Width (meter)	Enlargement Ratio (meter/meter)
3	0.28	2.74	2.9	1.06
4	0.79	4.27	15.2	3.56
6	0.36	4.57	9.5	2.08

significant at the 95% level. The fraction of the Good Hope watershed covered with impervious surfaces prior to development was 1.4%. Using Equation (3) to compute the cross-sectional areas for the 1951 channel yields enlargement ratios of 1.3-2.4, with an average value of 1.7 (Table 3). When Equation (3) is used to reproduce each cross-sectional area determined using the 1996 field survey data (Figure 8), the computed areas for the Good Hope Tributary have a root mean square error of 23%. Estimates of 1951 channel

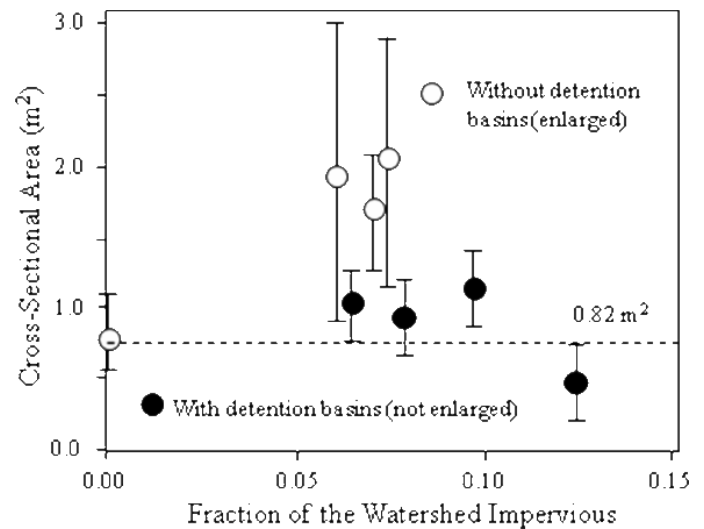


FIGURE 7. Average Cross-Sectional Areas of First-Order Tributaries of the Good Hope Tributary as a Function of the Impervious Fraction of the Watershed in 1996. Error bars represent two standard deviations computed from five cross-sections in each tributary (Table 3). Data are divided into two categories: channels with detention basins, and channels lacking detention basins. The area of the first-order tributary without development ( $0.82 \text{ m}^2$ ) (shown in gray) is taken to be the area of all first-order tributaries in 1951.

areas and enlargement ratios are subject to similar errors. Additional details of these computations are provided by Allmendinger (1999).

### Sediment Storage on Floodplains

Seventy-five trees that were growing on the valley flat ranged in age from 12 to 111 years. Accumulation rates on the valley flat decrease with distance from the channel (Figure 9): accumulation rates average around  $2 \text{ mm/year}$  within 2 meters of the channel to  $0.7 \text{ mm/year}$  14 meters from the channel. Accumulation rates on active floodplains formed through lateral migration (Figure 4) are not significantly different from accumulation rates on the immediately adjacent valley flat.

Sediment storage on active floodplains in the Good Hope Tributary main channel was assessed in detail by Allmendinger (1999). The ages of trees on these landforms indicated that the active floodplains all formed after 1951, and they therefore represent stored sediment that potentially could be included in our budget. However, Allmendinger (1999) also surveyed the volumes of the active floodplains, and his results indicate that the amount of sediment stored in active floodplains is an order of magnitude smaller than the other components of the sediment budget. As a result, storage on active floodplains is neglected here.

TABLE 3. Cross-Sectional Area Enlargement Predictions for the Main Channel and Selected First-Order Tributaries of the Good Hope Tributary.

Location	Drainage Area (km <sup>2</sup> )	Fraction Impervious	Average 1996 Cross-sectional Area (m <sup>2</sup> )	Standard Deviation (m <sup>2</sup> )	Average 1951 Cross-sectional Area (m <sup>2</sup> )	Enlargement Ratio
1	2.080	0.081	5.41	1.03	2.29	2.4
2	2.186	0.084	4.93	0.25	2.38	2.1
3	2.570	0.090	3.83	0.80	2.52	1.5
4	2.885	0.086	4.68	0.51	2.95	1.6
5	2.898	0.085	3.90	0.13	2.96	1.3
6	3.960	0.076	5.39	1.80	3.84	1.4
7	4.004	0.076	5.15	0.01	2.87	1.8
8	4.025	0.076	6.62	0.92	3.89	1.7
9	4.046	0.076	5.69	0.65	3.91	1.5
Tributary D	*	0.070	1.68	0.41	1.06	2.1
Tributary C	*	0.059	1.94	1.04	1.06	2.4
Tributary H	*	0.073	2.03	0.87	1.06	2.5
Tributary B	*	0.000	0.82	0.25	0.82	1

Note: Cross-sectional areas of the channel in 1951 are computed using Equation (3). \*Regression analysis shows that drainage area is not a significant variable for predicting cross-sectional enlargement in first-order tributaries.

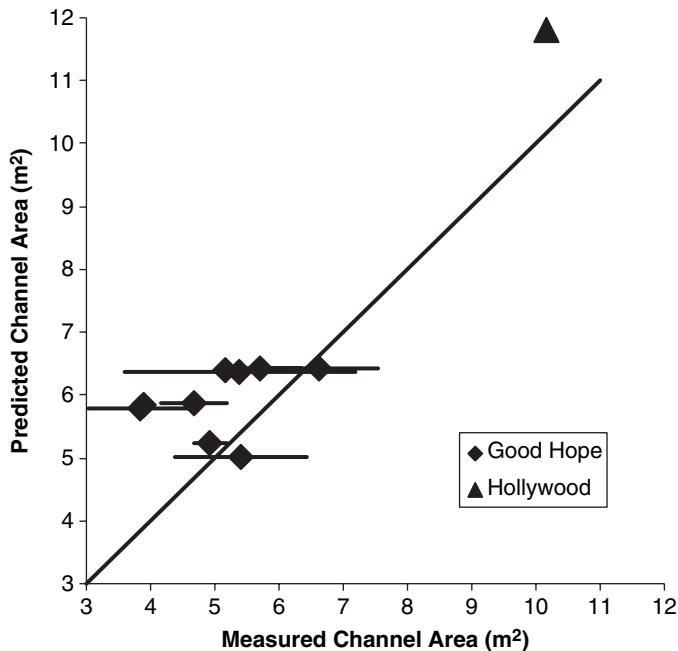


FIGURE 8. Measured Channel Cross-Sectional Area *vs.* Cross-Sectional Areas Predicted Using Equation (3) for the Good Hope and Hollywood Tributaries. Error bars represent two standard deviations computed from the measured cross-sections at each location (Figure 1).

### The Sediment Budget

The sediment budget is summarized in Figure 10, which gives the results as volumes and also as fractions of the total sediment yield of the watershed. Upland sediment production related to construction in the Good Hope watershed contributed 5,700 m<sup>3</sup> (equivalent to 70% of the sediment yield of the

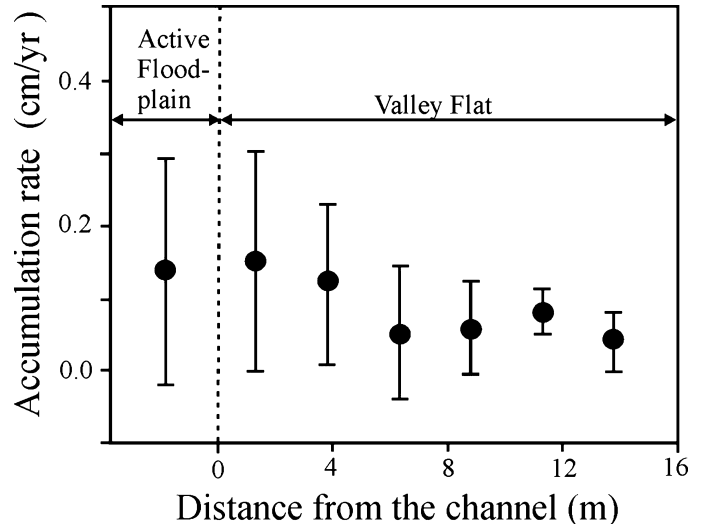


FIGURE 9. Average Floodplain Accumulation Rate in the Good Hope Tributary as a Function of the Distance From the “Edge of the Channel” (note that according to Figure 4, the Edge of the Channel corresponds to the edge of the valley flat). Locations of the “active floodplain” and “valley flat” are illustrated in Figure 4 and explained in the text. Error bars indicate two standard deviations about the mean measured values in each increment of distance from the channel (as discussed in the Methods).

watershed) to the sediment budget from 1951 to 1996. The enlargement of first-order channels has contributed 3,200 m<sup>3</sup> (equivalent to 40% of the sediment yield). These two sources contributed a total of 8,900 m<sup>3</sup> to the main channel of the Good Hope Tributary, a volume that actually exceeds the total sediment yield of the watershed. Enlargement of the main channel has contributed 3,200 m<sup>3</sup>, remarkably (and likely coincidentally) equal to the volume

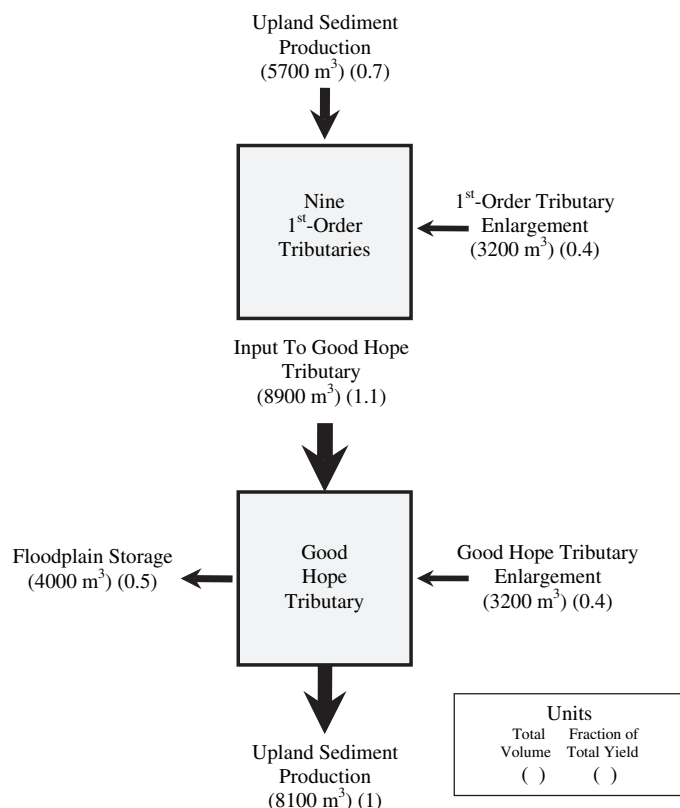


FIGURE 10. Sediment Budget for the Good Hope Tributary Watershed, 1951-1996.

contributed by tributary enlargement. Slightly more sediment, about 4,000 m<sup>3</sup>, was stored on the floodplain of the Good Hope Tributary (equivalent to approximately half of the sediment yield from the watershed). By solving Equation (1), the output of sediment from the Good Hope Tributary for 1951-1996 is estimated as 8,100 m<sup>3</sup>.

To provide a basis for comparison with other studies, the volumetric sediment yield can be converted to an annual mass flux using a nominal value of 30% for the porosity of eroded and deposited sediments and a value of 2,600 kg/m<sup>3</sup> for the density of the sediment. These computations result in an annual sediment yield of 135.0 tons/km<sup>2</sup>/year.

## DISCUSSION

### *Accuracy of the Sediment Budget Estimates*

While it is probably impossible to quote precise error estimates for the sediment budget computations of Figure 10, it is important to provide some assessment of their accuracy, and to use this assessment to

evaluate both the methods used and the results obtained.

We used a regression equation and land use data for each year from 1951 to 1996 to estimate upland sediment supply. We assume that determining the percentage of land under construction in the watershed is subject to relatively minor errors (Moglen *et al.*, 2004). However, the use of the regression equation is less precise. With approximately 50% unexplained variance, and the use of this equation over 45 individual years, significant errors are likely to propagate. Assuming (simply for illustrative purposes) that errors are normally distributed (Topping, 1972), a 50% error for one year will result in an accumulated error of approximately 340% over 46 years. Clearly, our estimate of upland sediment supply is likely to be only accurate to within about half an order of magnitude.

A similar approach was used by Allmendinger (1999, 2004) to assess the potential errors associated with the use of the regression equation presented here as Equation (3) to assess main channel enlargement. As illustrated in Figure 8, Equation (3), when used to reproduce cross-sections surveyed in 1996, has a root mean square error of 23%. For determining the 1951 channel areas, Equation (3) cannot possibly be more accurate than this, and therefore this estimate provides an upper bound on the precision of the computations of sediment production caused by main channel enlargement.

The present variability in channel morphology of first-order tributaries, as illustrated by the error bars in Figure 7, provides some useful information regarding the precision of enlargement estimates for first-order tributaries. Allmendinger (1999, 2004) computed the standard deviation of cross-sectional areas of enlarged and "nonenlarged" first-order tributaries, and following the rules of error propagation (Topping, 1972), estimated an error of 35% for the estimated volume of sediment produced by first-order tributary enlargement.

Estimates of sediment storage on active floodplains are subject to several random and systematic errors. Random errors may be potentially assessed by the inherent variability in the observed rates (although these may be caused by systematic, nonrandom processes as well). This variability is illustrated by the error bars in Figure 9. Allmendinger (1999, 2004) computed the standard deviations of the estimated accumulation rates, and once again following the rules of error propagation, he estimated errors of approximately 50%. Allmendinger (1999, 2004) did not consider potential errors caused by *in situ* deposition of organic matter from leaves, which could accumulate over the roots of trees and be spuriously included as overbank deposition. Although we cannot

rigorously address this issue quantitatively, we have assessed the contribution of *in situ* organic matter production on a flat upland terrace in the Shenandoah valley of Virginia (Pizzuto *et al.*, 2006). At this humid temperate site, *in situ* organic matter production accounted for approximately 0.5 mm/year. If a similar value applies to the Good Hope Tributary, then our estimates of floodplain storage should be reduced by about 50%.

Given that all of these errors propagate into our estimate of sediment yield, the final value of sediment production from the Good Hope Tributary may be slightly better than half an order of magnitude estimate. We argue below, however, that these estimates are nonetheless valuable.

#### *Justification for Ignoring Sediment Storage on the Bed of the Channel*

While designing our study, we did not explicitly include changes in storage on the bed of the stream between 1951 and 1996. We justified this assumption because other researchers, notably Costa (1975), made similar assumptions. However, our results can be used to demonstrate that our methods implicitly include changes in storage of the bed.

Consider a rectangular channel with width  $W$  and depth  $D$ . The channel area is  $WD$ . Also, define the enlargement ratio,  $ER$ , as the ratio of channel area,  $A$ , at times 1 and 2:

$$ER = A_2/A_1 \quad (4)$$

Substituting the definition of  $A$  into Equation (4) leads to

$$ER = \frac{W_2 D_2}{W_1 D} \quad (5)$$

Allmendinger (1999) demonstrated statistically that the channels of the study area, regardless of the level of urbanization, and hence channel enlargement, have similar ratios of width to depth. This suggests that channel enlargement is an allometric process such that the channel form remains constant as channel enlarge their cross-sectional areas, implying that

$$\frac{W_2}{D_2} = \frac{W_1}{D_1} \quad (6)$$

Equations (4-6) can be used to derive specific relationships for changes in width and depth as a func-

tion of the enlargement ratio of the channel and the observed width and depth surveyed in 1996:

$$\Delta W = W_2 \left( \frac{\sqrt{ER} - 1}{\sqrt{ER}} \right)$$

$$\Delta D = D_2 \left( \frac{\sqrt{ER} - 1}{\sqrt{ER}} \right)$$

These equations are used, along with the enlargement ratios summarized in Table 3, to estimate the average changes in channel cross-sectional geometry that have occurred in the Good Hope Tributary main channel from 1951 to 1996 (Figure 11). Figure 11 also includes an estimate of changes in the elevation of the floodplain through overbank deposition based on the measured levee sedimentation rate presented in Figure 9. The results of Figure 11 suggest that changes in channel area include both bed and bank erosion, and clearly our estimates of channel enlargement include, at least implicitly, both of these processes. Of course, the channel of the Good Hope Tributary is not rectangular. However, our conclusions are not sensitive to the cross-sectional geometry of the channel. For example, Allmendinger (1999) presents a similar analysis for triangular channels

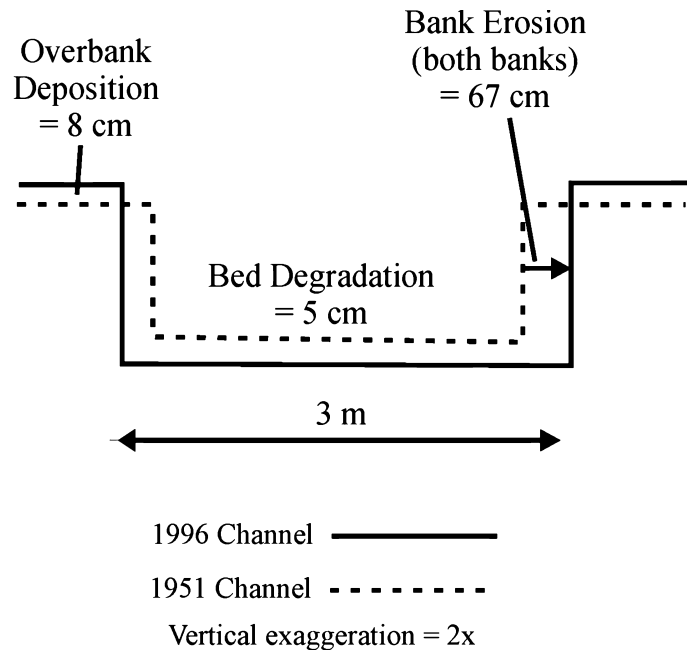


FIGURE 11. Illustrative Changes in Channel Cross-Sectional Geometry of the Good Hope Tributary Between 1951 and 1996. Values shown are computed for a 1996 channel with a width of 3 meters and a depth of 0.6 meters. The 1951 channel illustrated represents the average for all the enlargement ratios of Table 3.

with active floodplains similar to those illustrated in Figure 4. His results are essentially identical (though mathematically more complex) to those presented here.

### *Utility of the Sediment Budget*

In the Introduction, we argued that the primary goal of our study was to establish the significance of the sediment budget components we investigated. That is, the questions we set out to answer involve evaluating whether upland sediment supply, channel enlargement, and floodplain storage have been important components of the sediment budget of the Good Hope Tributary watershed.

What is the necessary and sufficient precision of sediment budget estimates required to establish “significance?” According to Reid and Dunnne (2003), “an evaluation of how the sediment budget results are to be used also leads to definition of the minimum level of precision required.” We argue that sediment budget components in a study such as ours can be considered “significant” if they are all the same order of magnitude, even though all the estimates are of low precision. According to this criterion, upland sediment supply, erosion of the channel boundaries, and floodplain storage are all important sediment budget components in the Good Hope Tributary from 1951 to 1996, and each component should be considered in developing strategies to predict and manage sediment production and ultimately, the sediment yield from the watershed. Additional studies with different goals might well require considerably greater precision. For example, an effort to evaluate different management strategies for controlling sediment yield would likely require more detailed and accurate studies.

### *Contributions From Erosion of “Legacy” Sediments*

The erosion of floodplains storing sediment derived from the “Agricultural Age” (otherwise known as “legacy” sediment) is increasingly viewed as an important water quality problem (Merritts *et al.*, 2005, 2006; Smith, 2006). These sediments are suspected of having high nutrient concentrations, raising concerns regarding eutrophication of receiving water bodies (such as the Chesapeake Bay) (Kemp *et al.*, 2005) and elevated regional sediment yields (Gellis *et al.*, 2005; Merritts *et al.*, 2005).

Lewicki (2005) mapped the locations of buried pre-settlement soil horizons in four exposed river banks of the Good Hope Tributary (and of other watersheds nearby). At these locations, post-settlement “Agricultural Age” deposits comprised 50, 40, 58, and 53% of

the total height of eroding banks. The average value is 50%.

These data provide the basis for some interesting, though speculative, approximate estimates of the contribution of Agricultural Age deposits to the total sediment yield of the Good Hope Tributary. If the average value of 50% is extended to all the eroding banks of the Good Hope Tributary, and if all the sediment produced by channel enlargement stems from bank erosion (clearly a maximum estimate, according to Figure 11), then 50% of the total sediment produced by channel enlargement could be composed of Agricultural Age deposits, equivalent to a volume of 1,600 m<sup>3</sup> (Figure 10). Overbank deposits stored a total of 4,000 m<sup>3</sup> of sediment between 1951 and 1996, so it is possible (though unlikely) that none of these sediments actually left the watershed during this time.

These figures can be used to estimate a reasonable range of possible contributions from eroded Agricultural Age deposits to the sediment yield of the Good Hope Tributary. If all of these deposits were stored on the floodplain, then the contribution is clearly zero. On the other hand, if none of these deposits were stored on the floodplain, then Agricultural Age deposits could have comprised 20% of the total sediment yield of the watershed. Clearly, erosion of “legacy” sediments has not dominated the sediment yield of the Good Hope Tributary from 1951 to 1996.

### *Comparison With Other Studies*

When compared with watersheds in other parts of the U.S., the Good Hope Tributary watershed has produced a relatively large amount of sediment. The data in Table 4 suggest that sediment yield from the Good Hope Tributary over the last 45 years is almost eight times greater than the average for streams along the Atlantic coast. The data also suggest that the sediment yield from the Good Hope Tributary is greater than mid-Atlantic Piedmont watersheds with forested land use and about equal to that of watersheds with rural land use. Suburban watersheds that are being actively developed without stormwater management yield much more sediment than the Good Hope Tributary.

Wolman (1967) presented a frequently cited curve of annual sediment yield for mid-Atlantic watersheds that spans several periods of changing land use from the 1700s through the mid-20th Century. Wolman (1967) suggested that sediment yields should increase dramatically during periods of construction, reaching values exceeding 200 tons/km<sup>2</sup>/year in the absence of sediment management practices. Following development, sediment yields should become significantly

TABLE 4. Comparison of the Sediment Yield of the Good Hope Tributary With Other Data.

River or Region	Sediment Yield (tons/km <sup>2</sup> /year)	Drainage Area (km <sup>2</sup> )	Sediment Discharge (tons/year)
Colorado River*	0.2	$6.3 \times 10^5$	$1.3 \times 10^5$
St Lawrence River*	4.0	$1.0 \times 10^6$	$4.1 \times 10^6$
Helton Branch, Sommerset, Kentucky (wooded)**	6.0	2.0	13.0
Columbia River*	12.0	$6.9 \times 10^5$	$8.3 \times 10^6$
U.S. Atlantic Coast*	17.0	$7.4 \times 10^5$	$1.2 \times 10^7$
Gulf Coast*	59.0	$4.5 \times 10^6$	$2.7 \times 10^8$
Georges Creek at Franklin, Maryland (rural)**	80.0	188.0	$1.5 \times 10^4$
Gunpowder Falls, Towson, Maryland (rural)**	90.0	777.0	$7.0 \times 10^4$
Seneca Creek, Dawsonville, Maryland (rural)**	124.0	262.0	$3.2 \times 10^3$
Monocacy River, Frederick, Maryland (rural)**	126.0	$2.1 \times 10^3$	$2.7 \times 10^5$
Good Hope Tributary	135.0	4.0	$1.4 \times 10^3$
Anacostia River near Colesville, Maryland (rural)**	181.0	55.0	$1.0 \times 10^4$
Rest of Western U.S.*	193.0	$3.2 \times 10^5$	$6.2 \times 10^7$
Gunpowder Falls, Hereford, Maryland (rural)**	193.0	207.0	$4.0 \times 10^4$
Watts Branch, Rockville, Maryland (rural)**	199.0	10.0	$1.9 \times 10^3$
Greenbelt Reservoir, Greenbelt, Maryland (suburban)**	$2.2 \times 10^3$	2.0	$4.7 \times 10^3$
Tributary, Gwynns Falls, Maryland (suburban)**	$4.4 \times 10^3$	0.2	$1.1 \times 10^3$
Tributary, Kensington, Maryland (suburban)**	$9.3 \times 10^3$	0.2	$2.2 \times 10^3$
Lake Barcroft, Fairfax, Virginia (suburban)**	$1.3 \times 10^4$	25.0	$3.1 \times 10^5$

\*Milliman and Meade, 1983.

\*\*Wolman and Schick, 1967.

lower, leveling off to slightly greater than 10 tons/km<sup>2</sup>/year. Allmendinger (1999, 2004) noted that the 45-year average sediment yield of 135 tons/km<sup>2</sup>/year obtained during this study represents an intermediate value between these two extremes. This is consistent with Wolman (1967) results, because the period between 1951 and 1996 included brief periods of extensive construction as well somewhat longer periods when relatively few areas were under construction.

**Management Implications.** We have quantified three important components of the sediment budget of the Good Hope Tributary between 1951 and 1996: upland sediment production, channel enlargement (of both first and higher order channels), and floodplain storage. All of these components can be considered to be approximately equal in magnitude given the precision of the methods used.

These results have several important implications for sediment management practices. First, efforts to reduce sediment yield will require policies that consider many different watershed components. Best management practices designed to reduce upland sediment yield will have no effect on channel erosion. Restoration of eroding channel banks will not influence the substantial amount of sediment supplied from upland sources. Finally, discussions of sedimentation problems by watershed managers and others tend to ignore floodplain storage. In the study area from 1951 to 1996, floodplains have stored approximately one-third of the total sediment produced,

which is clearly a significant amount. These deposits, of course, will eventually be remobilized by channel erosion in coming decades and centuries. Programs to reduce the input of sediment and associated nutrients to downstream water bodies should account for floodplain storage, as this process will greatly lengthen the time needed before improved upland management practices can secure improvements in water quality downstream.

## CONCLUSIONS

Empirical equations relating channel form to the extent of urbanization, dendrochronology, and survey and grain size data, are used here to estimate changes in the morphology and sediment budget of the Good Hope Tributary from 1951 to 1996. During this period, the percentage of the watershed covered with impervious surfaces increased from 1.7 to 7.5% and the channel area of the Good Hope Tributary increased by factor of 1.7. A sediment budget indicates that upland erosion and channel enlargement were significant sources of sediment in the watershed, each producing an amount of sediment equivalent to 70 and 80% of the total sediment yield. Floodplain sediment storage accounted for 50% of the total sediment yield, demonstrating that floodplains are an important component of the sediment budget of the study area during recent urban development.

Solving a simple mass balance equation suggests that the sediment yield of the Good Hope Tributary is equivalent to 135.0 tons/km<sup>2</sup>/year.

Stratigraphic studies published elsewhere and our own field observations demonstrate that extensive deposition occurred across the floodplain of the Good Hope Tributary during the 19th Century. Erosion of these “legacy” sediments accounts for between 0 and 20% of the total sediment yield of the watershed. These results do not support the hypothesis that erosion of stored “Agricultural Age” deposits is responsible for elevated sediment yields in the region.

We have completed our analysis without observational data spanning the entire period represented by our sediment budget. Our estimates are of low precision, with expected errors of individual sediment budget components possibly exceeding 100%. Nonetheless, all of the components of the sediment budget are likely to be significant, and all are of similar magnitude. Future watershed management programs to control sediment production and sediment yield should be designed to specifically address upland erosion, erosion of channel boundaries, and sediment storage on floodplains.

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